# Large-Eddy Simulations of Internal Hydraulic Controls

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## LONG-TERM GOALS

Through the combined use of field measurements and numerical modeling, I wish to develop an understanding and parameterization of mixing processes in shallow water, specifically, on continental shelves, in straits, and inshore waters.

## OBJECTIVES

I am working towards a quantification of turbulence and mixing at an internal hydraulic control by comparing large-eddy simulations of an idealized two-layer contraction control with observations from the Bosphorus Straits. The objectives of the current project are assessing where mixing is strongest, determining the quantity and composition of the mixed fluid produced, and how the larger-scale flow is modified relative to inviscid theory owing to turbulence at the hydraulic control.

## APPROACH

In collaboration with Dr. Kraig Winters of the Applied Physics Laboratory, University of Washington, a large-eddy simulation designed to study the influence of topography on stratified fluid flows has been developed and configured to study an internal hydraulic contraction control (Winters et al, 1999). The basic characteristics of the contraction were motivated by the central contraction of the Bosphorus Straits. A scheme has been developed which permits the model forcing to be specified by a density contrast and an along-channel barotropic pressure gradient, allowing the use of a limited domain to simulate the exchange between two reservoirs without having to specify the reservoir conditions.

Simultaneous with this effort, a series of observations collected in the central contraction of the Bosphorus Straits (Gregg et al., 1999) were analyzed, focusing on the developing a description of the density and flow fields that could be compared with the large-eddy simulation results. Of the various parameters measured, the initial emphasis was on the salinity, temperature, density and current fields. Dissipation rate estimates are still being finalized because of various difficulties in operating the microstructure profiler in the Straits (Gregg, pers. comm.).

High frequency acoustic backscatter also was measured during the field work. Previous studies (Goodman, 1985; Seim et al., 1995) have suggested that turbulent microstructure may produce significant acoustic backscatter in regions of strong vertical density gradient. The backscatter imagery collected in the Bosphorus Straits is very rich in detailed structure and often intense where dissipation rates were largest. To further explore the possibility that the acoustic imagery may provide a remotely-sensed measure of turbulence, theory was developed to better predict the acoustic backscatter intensity in a stratification regime dominated by the salinity field like that in the Bosphorus (Seim, 1999). The observations can then be converted to volume scattering strengths, and by using the dissipation measurements, compared with the theoretical predictions.

**WORK COMPLETED**

A series of numerical simulations have been carried out to explore changes in the nature of the hydraulic control as the ratio of volume fluxes in the upper and lower layers are varied, and under slip and no-slip bottom boundary conditions. Details of this effort are given in Winters and Seim (1999) and discussed below. Further modeling is focusing on assessing the sensitivity of turbulence generated in a contraction to changes in the channel geometry. In particular, we are exploring the aspect ratio of the channel and channel curvature, two distinguishing features of the central contraction of the Bosphorus that were not captured in the initial modeling exercise.

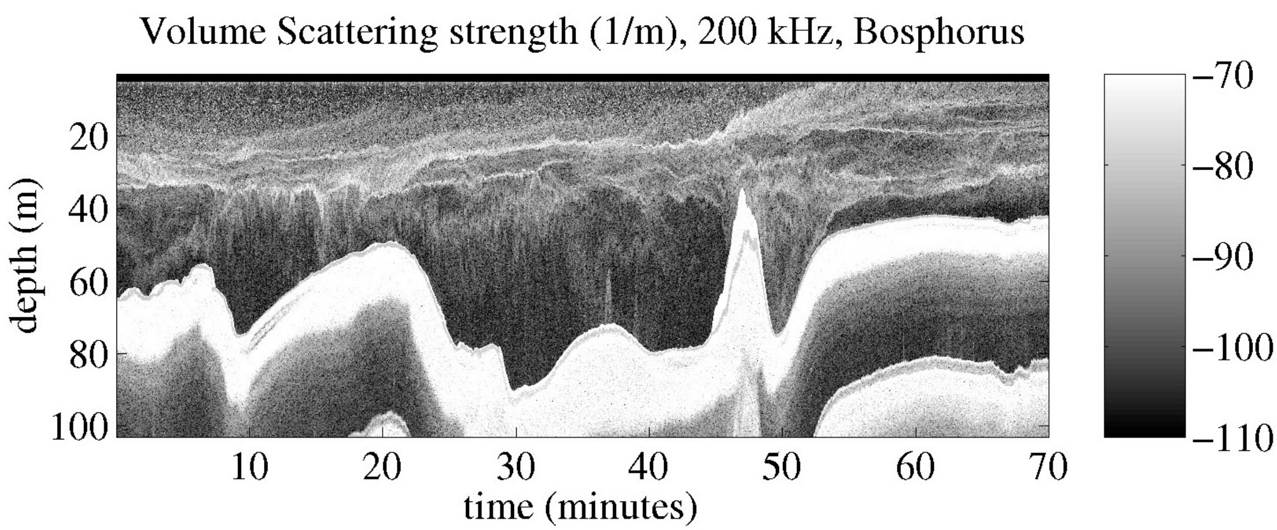


***Figure 1: Volume scattering strength in dB at 200 kHz in the central contraction of the Bosphorus computed from acoustic observations. The bright white band at 50-90 m depth is the bottom. Values exceed –70 dB in the interfacial layer (20-40 m depth), consistent with preliminary estimates of the strength of scattering due to turbulence (Seim, 1999).***

Analysis and synthesis of the observations from the central contraction has led to a three-dimensional description of the central contraction in the Bosphorus, where vertical variations are treated as either a two-layered or three-layered flow. The comparison of the LES results with observations continues. A synthesis of the modeling and observations was presented at the IUGG conference held in Birmingham, England in July, 1999 (*Seim, H. E. and K. Winters, A comparison of large-eddy simulations with observations from the central contraction in the Straits of Bosphorus*), and a draft manuscript is underway.

Theoretical development of how the inclusion of salinity alters the acoustic backscatter intensity spectrum is complete. Conversion of the observations to volume scattering strengths is on-going (Figure 1); difficulties in adjusting for some system components have caused delays. Theory-based predictions of the scattering strength must await completion of the dissipation rate profile processing.

**RESULTS**

Numerical investigations of turbulence and mixing at a contraction control indicate that a significant fraction of the fluid participating in the exchange flow undergoes mixing. Though the result is sensitive to the turbulent parameterization scheme used, we find that as much as 50% of the fluid in a layer is modified in transiting the hydraulic control. Under free-slip bottom boundary conditions, the hydraulic control maintains the characteristics of a maximal exchange flow identified by Armi and Farmer (1986), that of a subcritical flow regime bounded on either side by regions of supercritical flow. Quantitatively, in a viscous flow the locations of the control points are shifted outward from the center of the contraction relative to predictions from inviscid theory.

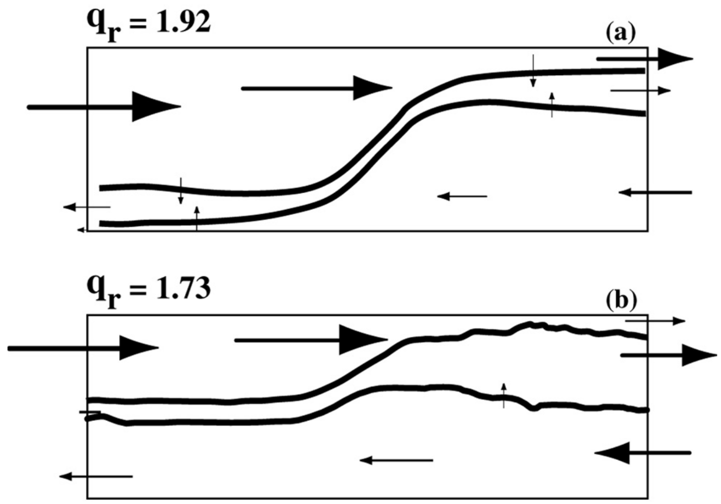


***Figure 2: Schematic representation of fluxes for (a) free-slip and (b) no-slip conditions. Shown is a vertical slice through a channel that is thinnest in the middle of each section. In both cases the net flow is from left to right. Dark lines define the boundaries between the three layers of the flow. In (a) a maximal exchange flow is achieved, the interface is deflected to both sides of the contraction, and the interfacial layer carries a significant fraction of the flow in both directions. In (b) bottom friction inhibits the development of supercritical flow in the lower layer and a submaximal exchange flow develops. The interface is deflected only downstream of the contraction, and is essentially undisturbed upstream of it. The interfacial layer occupies nearly half of the water column downstream of the contraction and carries the majority of the transport.***

We find that the density and velocity field are best described as having three layers in the vertical, the two layers of unmixed reservoir fluid bounding an interfacial layer of mixed fluid produced by turbulent mixing within the contraction. The interfacial layer is an active participant in the exchange flow, carrying 30-50% of the transport. Changes in transport in the interfacial layer are concentrated in the contraction itself, indicating turbulent mixing is highly localized at the hydraulic control. Considering the along-channel transport in the interfacial layer, we find the flow to be divergent, flowing away from the center of the contraction in either direction (Figure 2a).

In our simulations with a no-slip bottom boundary condition there is a fundamental change in the hydraulic state of the flow. A maximal exchange flow was no longer achieved because flow in the lower layer never reaches critical conditions. Instead, a submaximal exchange flow (Armi and Farmer, 1985) is realized in which flow is supercritical only downstream of the contraction with respect to the upper layer. This case generates intense mixing downstream of the contraction, causing the interface to carry the majority of the upper layer transport (Figure 2b). Though obviously bottom friction does not always cause a shift away from maximal exchange conditions, our results indicate they can. Clearly, submaximal conditions can be achieved in ways other than flooding the control points by changing reservoir conditions. A local frictional influence can also produce submaximal exchange conditions.

Observations from the central contraction of the Bosphorus resemble the submaximal no-slip bottom boundary condition case. In the Bosphorus the upper layer and interfacial layer thicknesses change dramatically but the lower layer thickness changes little. The density of the interface decreases as it thickens, implying preferential entrainment of upper layer fluid. The inference is that local frictional influences may lead to submaximal exchange conditions in the central contraction.

A characteristic of the observations not consistent with the numerical simulations is the flow direction of the interfacial layer. In the Bosphorus, this layer moves northward against the upper layer, whereas in the simulation the interfacial layer flows with the upper layer. A possible explanation for this discrepancy is the geometry of the channel; in the simulation the upper and lower layers are the same width, whereas in the Bosphorus the channel possesses a deep mid-channel notch flanked by shallow banks, effectively channelizing the lower layer flow. Maximum flow speeds occur in the lower layer, and we hypothesize that the momentum from this layer dominates the interfacial layer. Despite the large flow speeds the lower layer remains subcritical because of the thickness of the layer. Strong entrainment from the upper layer and northward flow in the interfacial layer suggests considerable recirculation at the contraction.

**IMPACT/APPLICATIONS**

Our findings of significant production of mixed fluid at hydraulic controls, and that the interfacial layer is an integral part of the exchange flow, are consistent with and provide a dynamical explanation for similar results in the observational study of Gibraltar by Bray et al. (1995). Recognition that intense mixing can be highly localized is an important step forward in our understanding of mixing processes in straits, and further analysis will likely lead to a parameterization of turbulent mixing in these settings.

The other major finding is that bottom friction can shift the solutions to a submaximal exchange state. That these solutions are possible without flooding the hydraulic controls may help explain the number of observations in shallow water of hydraulic-like phenomena that fail to resemble maximal exchange flows.

**TRANSITIONS**

Mike Gregg is considering the implications of our results in his analysis of datasets from the Bosphorus Straits and in Knight Inlet where the hydraulic state of these systems is an unresolved issue. A suite of software tools to utilize acoustic doppler current profiler (ADCP) observations in real-time, developed for use the in the coastal mixing and optics (CMO) experiments, has now be used extensively in estuarine settings to achieve high horizontal spatial resolution. The software is also being used by several groups associated with US Globec to process shipboard ADCP data.

## RELATED PROJECTS

Much of this work has been carried out in collaboration with Winters and Gregg. Cudaback (1998) has developed a three-layer model in her work on the Columbia River that is quite similar to the three layer analysis we used in the analysis of simulation and observations. She is using a simple entrainment law for the interfacial layer at present, but her model would be an excellent testbed for parameterization schemes.

The ADCP software was used to process data from the Ledwell/Duda/Oakey CMO cruises and analysis of those observations continues.

## REFERENCES


Armi and D. Farmer, 1986. Maximal two-layer exchange through a contraction with barotropic net flow. J. Fluid Mech. 164:27-51.

Bray, N. A., J. Ochoa and T. H. Kinder, 1995. The role of the interface in exchange through the Strait of Gibraltar. J. Geophys. Res. 100: 10,755-10776.

Cudaback, C, 1998. The effect of vertical mixing on along channel transport in a layered flow. Ph.D. dissertation, Univ. of Washington, 128 pp.

Goodman, L. , 1990. Acoustic scattering from ocean microstructure. J. Geophys. Res.. 95:11,557-11,573.

Gregg, M.C. szoy, E. and M. A. Latif, 1999. Quasi-stedy exchange flow in the Bosphorus. Geophys. Res. Let. 26:83-86.

Seim, H. E., M. C. Gregg and R. T. Miyamoto, 1995. Acoustic backscatter from turbulent microstructure. J. Atmos. Ocean. Tech.. 12:367-380.


## PUBLICATIONS


Seim, H. E., Acoustic backscatter from salinity microstructure, J. Atmos. Ocean. Tech., in press.

Winters, K. and H. E. Seim, The role of dissipation and mixing in exchange flow through a contracting channel, J. Fluid Mech., in press.

Winters, K., H. E. Seim, and T. D. Finnigan, Simulation of non-hydrostatic, density-stratified flow in irregular domains, Inter. J. Num. Meth. Fluids, in press.

Winters, K. B. and H. E. Seim, 1998, Exchange flows through contracting channels: entrainment and mixing, *Proceedings of the 13th Australasian Fluid Mechanics Conference, Monash University, Melbourne, Australia*